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PHOTON LOSSES IN COSMIC RAY ACCELERATION IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The usual assumption of the acceleration of ultrahigh energy cosmic rays, $> 10^{18}$ eV in quasars, Seyfert galaxies, and other active galactic nuclei is challenged on the basis of the photon interactions with the accelerated nucleons. This is similar to the effect of the black body radiation on particles $>10^{20}$ eV for times of the age of the universe except that the photon spectrum is harder and the energy density greater by $\sim 10^{13}$. Hence, a single traversal, radial or circumferential, of radiation whose energy density is no greater than the emitted flux will damp an ultrahigh energy cosmic ray 10^{20} eV by greater than 10^{4} times its energy. Hence, it is unlikely that any reasonable configuration of acceleration can avoid disastrous photon energy loss. A different site for ultrahigh energy cosmic ray acceleration must be found.

INTRODUCTION

Ultrahigh energy cosmic rays, $E \gtrsim 10^{18}$ eV, are almost universally assumed to originate outside the Galaxy and then diffuse in. This is because their larmor orbit in the field of the Galaxy becomes of the order of the dimension of the Galaxy, 10 kpc, at 3×10^{19} eV. There is thus no way for such particles to be contained within the galaxy for extended periods. Hence, the usual assumption is that they diffuse into the galaxy from intergalactic space filled from an unknown source. Such an unknown source has been plausibly assumed to be within the extreme energetic phenomena of quasars or active galactic nuclei (AGN).

In a companion article in this volume, Hillas has shown that the acceleration of such particles by the more recent mechanism of collisionless plasma shock acceleration is very unlikely in any known extragalactic phenomena. This is because plasma shock acceleration requires a particle to diffuse in momentum space. Because the dimension of each diffusion step is several larmor radii and very many steps are required for low β shocks ($\beta = V/c$) the necessary time and distance traversed by the shock becomes too large for the acceleration of ultrahigh energy cosmic rays in any proposed or observed extragalactic sites. Here it is shown that acceleration in active galactic nuclei or quasars (AGN) is nearly impossible because of radiation damping of the accelerated high energy particle by photons on the way out of the object. Ginzburg and Syrovatskii[1], and Brecher and Burbidge[2] extensively reviewed the need for an extragalactic origin of the highest energy particles and further believe, as do many others, that observable extragalactic objects like AGN are the likely source. However, it is just the photons of this observability that are the problem.

PHOTON ATTENUATION

The very highest energy cosmic rays were inferred from air shower measurements (10^{19} to 10^{20} eV) and confirmed among various experiments.[3] Greisen[4] pointed out that such high energy particles in the extragalactic environment would lose their energy in a Hubble expansion time due to Doppler shifted collisions with the blackbody radiation. This is because a black body photon of 3 kT = 10^{-3} eV, T = 2.7 K, is Doppler shifted to 200 MeV for $\Gamma \simeq 1/\sqrt{1-\beta^2} = 10^{11}$ for $E = 10^{20}$ eV cosmic ray protons. Such collision between a photon and a proton produces π's and ence transfers significant momentum ($\simeq m_\pi \Gamma/c$) from the proton causing an energy loss. A similar loss occurs at lower energies $E \gtrsim 10^{18}$ eV due to $e^{\pm}$ pair production. If the primary cosmic ray is a nucleus of atomic weight A, and thus a lower value of Γ per nucleon, $\Gamma_N = \Gamma_p/A$, for a given shower energy, then gamma-ray nucleon processes would rapidly destroy, or spall, the nuclei for shower energies $\gtrsim 10^{19}$ eV total.

The predicted cutoff, around 10^{20} eV, is definitely not observed and indeed the spectrum becomes flatter above 10^{18} eV, the exact converse of the expectation. Very detailed calculations of spallation of nuclei due to infrared and star light, pair production and pion production were performed by Puget, Stecker, and Bredekamp.[5] Figure 1, reproduced from their article, shows the energy loss time due to the blackbody photons alone. The full radiation spectrum used for the spallation analysis is shown in Fig. 2. One notes that $e^{\pm}$ pair production from protons above $E > 2 \times 10^{18}$ eV reduces the CR lifetime to less than the Hubble expansion time 2×10^{10} y. As one goes to higher energy, 10^{20} eV the CR lifetime becomes progressively shorter ($\sim 10^{-2}$ Hubble time) due to pion production or for iron nuclei by pair production. This argument severely restricts the origin and lifetime of cosmic rays to dimensions of the local supercluster. In Fig. 2 the very weak photon flux in the infrared and optical causes Doppler shifted spallation of iron nuclei. This further limits the possible explanation of these ultrahigh energy cosmic rays to either protons or iron nuclei within the local supercluster.

However, the frequent assumption of acceleration in active galactic nuclei in the local supercluster has far worse limitations due to the same radiation damping.

ACCELERATION IN ACTIVE GALACTIC NUCLEI

The assumption of the acceleration of cosmic rays in quasars, BL lac objects, Seyfert galaxies, and AGN (active galactic nuclei) suffers in the extreme from the same problem of photon damping. The damping or deceleration occurs from the photon energy density of the emission by which we recognize the objects in the first place. A particle can be accelerated inside or outside such an object.

Inside or outside corresponds to the location of a radiation emission surface. In general the most energetic phenomenon should occur inside, but it would be possible for a particle to be accelerated outside in a magnetically confined orbit. Therefore the following alternate assumptions are made as applying to any reasonable mechanism of acceleration in any AGN:

1. The acceleration of a particle must take place within and the particle traverse at least one radius of the object, where the radius corresponds to an emission surface inside of which the photon flux is quasi-isotropic.
2. Acceleration outside an emission surface must require at least one orbit around the object in a presumed magnetic field strong enough to confine the high energy particle. Because of synchrotron radiation, the orbit must be larger than 10^{18} cm for $\Gamma > 10^{11}$; $R \gtrsim 3\Gamma_{11}^{3}$ pc.

Both circumstances lead to roughly the same impossible loss of the cosmic ray energy due to the two processes of pair production and pion production. In the first case of purely radial traversal of the emission nebula, the photons are quasi-isotropic in the rest frame and in the second case the photon streaming will lead to a primarily orthogonal flux, both of which lead to photon collision ener-

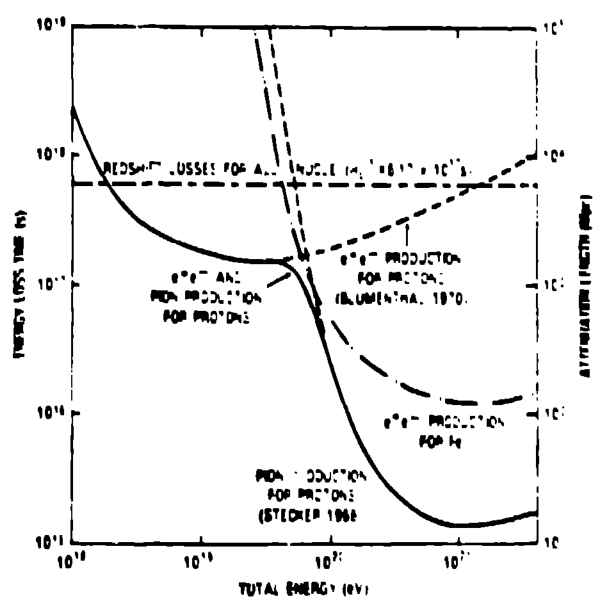

Fig. 1. From Puget et al (1976). The energy loss time and attenuation length for protons from pair production, redshift, and photo-pion production losses based on the calculations of Stecker (1968) and Blumenthal (1970). Also shown is the attenuation length for ^{56}Fe from pair production losses.

Stecker, F. W. 1971, Nature Phys. Sci., 234, 28.
Blumenthal, G. R. 1970, Phys. Rev., D1, 1596.

gies in the frame of the cosmic ray particle essentially the same as calculated by Puget et al.[7] It should be noted that one cannot use the radial photon flux external to the surface to significantly accelerate the particles further because of red shift and photon drag Noerdlinger.[6] Noerdlinger points out that the limiting Γ_{rad} from the acceleration of a particle by a near infinite plane parallel radiation source is proportional to $(\phi_{rad})^{\frac{1}{4}}$ and for all practical purposes limits $\Gamma_{rad} \lesssim 10$, or 10^{10} less than desired for CR's.

AGN RADIATION FLUX

For either radial or orthogonal acceleration one can scale the photon damping or cosmic ray energy loss to a standard AGN. For Seyfert Galaxies see Weedman,[7] BL Lacertae Objects Stein et al[8] and x-ray emission, Grusky and Schwartz.[9] The luminosity of AGN varies over a wide range from roughly 10^{44} to 10^{47} erg s^{-1} for Seyfert galaxies to the bright quasars. Similarly the fluctuation time varies from hours to a year (Schwartz et al.[10]). In general the most luminous objects like 3c273 have larger fluctuation times, and the weaker objects shorter fluctuation times. Therefore let the standard luminosity be $L_{46} = 10^{46}\Delta t_6$ erg s^{-1} and radius for a 10-day fluctuation period be $R_{16} = 3 \times 10^{16}\Delta t_6$ cm so that the photon energy flux at the surface becomes:

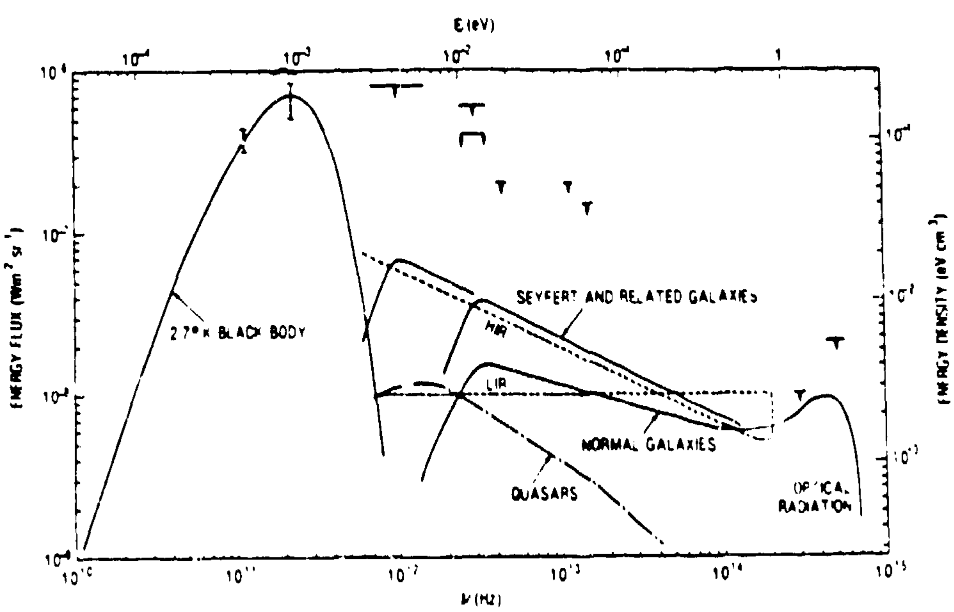

Fig. 2. From Puget et al (1976). Computed background radiation fields from quasars, Seyfert and related galaxies, and normal galaxies as discussed in the text. Also shown are the 2.7 K microwave and optical radiation fields as well as some measured values and upper limits. The dotted lines labeled HIR and LIR were taken as alternative models for the intergalactic infrared background fields used in the calculations. Quantities given are equivalent to spectral densities times frequency (Hz per Hz).

$$\phi = 3L/(4\pi R^2 = 10^{12}\, L_{46}\, \Delta t_6^{-1} \text{ ergs cm}^{-2} \text{ s}^{-1}. \tag{1}$$

In the above references, the spectrum of AGN also varies from object to object but in general the departure from a constant average energy flux per logarithmic band width, i.e., $d\phi/d[\ln(h\upsilon)]$ is small, no more than an order of magnitude from the IR to hard x-rays. Hence the differential flux per lograithmic band width is approximately:

$$d\phi \cong 10^{11}\, L_{46}\, \Delta t_6^{-1}\, d(\ln h\upsilon) \text{ ergs cm}^2 \text{ s}^{-1} \tag{2}$$

and the differential photon number density at the surface becomes

$$n_{h\upsilon}\, d(h\upsilon) \cong 6 \times 10^{12}\, L_{46}\, \Delta t_6^{-1} \frac{d[\ln(h\upsilon)]}{(h\upsilon)} \text{ cm}^{-3} \quad , \quad h\upsilon \text{ in ev.} \tag{3}$$

ENERGY LOSS TIME

The CR energy loss rate is:

$$dE/dt = -2\Gamma\langle E_\pi\rangle \int_{\text{threshold}}^{\infty} n_{h\upsilon}\sigma_\pi c\, d(h\nu) \tag{4}$$

where $\langle E_\pi\rangle$ is the average total pion energy in the proper frame $\cong 1/3$ GeV; then the loss time becomes:

$$\Delta t_{loss} = E/(dE/dt) = 1.5/[\int_{\text{threshold}}^{\infty} n_{h\upsilon}\sigma_\pi c\, d(h\upsilon)] \tag{5}$$

where $\langle\sigma_\pi\rangle = 4 \times 10^{-28} \text{cm}^2$, is peaked close to twice the pion production threshold.

The threshold energy for production of π's in the proper frame is E_π/Γ and the major contribution to the integral occurs at twice this energy or $3 \times 10^8/\Gamma$ eV. Hence the loss time becomes:

$$\Delta t_{loss} = 6 \times 10^{12} \Delta t_6/(L_{46}\Gamma) \quad \text{s} \quad . \tag{6}$$

where Δt_6 is the fluctuation time in 10^6 seconds. The energy losses are prohibitive where the loss time is the time for a particle to traverse the radius of the radiation surface layer of the AGN so that all particles whose energy is greater than $\Gamma_{max} = 6 \times 10^6/L_{46}$ or 6×10^{15} eV will lose their energy in one traversal of the radiant surface. Here L_{46} is a scaled (by Δt_6) standard AGN such that a Seyfert galaxy of fluctuation time of 10^4 seconds would correspond to a total luminosity of 10^{44} erg s^{-1}. Here we have assumed that the radiant energy density $n_{h\upsilon}$ is uniform inside the AGN. Any concentration of photon density towards the active center will only make acceleration still more difficult.

Finally we consider an orbit of a particle outside the radiant surface. As pointed out earlier this orbit must be at $R > 10^{18}$ cm ($B \lesssim 1_{gauss}$) for $\Gamma > 10^{11}$, 10^{20} cΔ CR's. This corresponds to a magnetic field energy $W_B = (B^2/8\pi)\, 4\pi R^3 \simeq 10^{53}$ ergs. For a dipole field $B\alpha R_c^{\ 3}$, R_c = central radius, so that the field energy $W_B = 10^{53}(10^{18}/R_c)^4$ ergs. Hence if the field is constrained at a radius inside the radiant surface, a likely circumstance, only the largest radiant surfaces i.e., where $\Delta t_6 \simeq 10$, will lead to a reasonable limit on field energy, i.e., a field energy small compared to the rest energy of the AGN $\lesssim 10^{64}(M_{AGN}/M_8)$ ergs. For this circumstance $\Delta t_6 \simeq 30$, i.e., a light year in radius and $L_{46} \simeq 10$, so that the cosmic ray particle of 10^{20} eV would have a loss time of $\sim 10^{-6}$ of an orbit period.

The spallation of heavy nuclei such as Fe would, of course, extend to the energy of the photo-nuclear threshold or a factor of 20 lower in energy.

The large photon damping of the acceleration of high energy cosmic rays is strongest for the highest energy particles in the most energetic quasars where the emission peaks at 10-100 microns at $L = 10^{47}$ ergs s^{-1} and the luminosity fluctuation time is a year. Here the damping time is 10^{-5} of the particle escape time at an energy of 10^{20} eV. Hence it seems unreasonable to expect ultrahigh energy cosmic ray acceleration in AGN.

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